DYNAMIC COMPRESSION MEMBERS

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Conventional compression members or struts are limited by the finite strength of available structural materials or by problems of twisting and buckling. However, structures utilising momentum support could have any strength up to the relativistic limit and need neither break nor buckle. They could also store large amounts of energy.

1. INTRODUCTION

The capability of conventional structural components to withstand great stress is limited by the finite strength of structural materials. This is determined by the strengths of chemical bonds. Materials available at present have specific strengths (strength/density) of the order of 1-10 $MN/m^2/(kg/m^3)$; for example, Kevlar-49 [1] has a specific strength of $(3.6GN/m^2)/(1450kg/m^3) \sim 2.5MN/m^2/(kg/m^3)$. This specific strength dictates the maximum force that can be transmitted a given distance with a given structural mass (MN m/kg); thus 1kg of Kevlar 1m long will carry no more than a 2.5MN load. The specific strength therefore also dictates the maximum amount of energy that can be stored in a flywheel of a given mass (MJ/kg), because if a hoop of 1m radius and mass 1kg/radian is spun at 1581m/s the tension, caused by the centripetal acceleration, v^2/r, is 2.5MN, and the kinetic energy is 1.25MJ/kg (note that the dimensions of specific strength and specific energy are actually the same, and correspond to the square of a velocity). If we try to increase the load on the cable or the spin of the flywheel above these limits the structure will fail. Compression members may fail by buckling or twisting even before these limits are reached. This is why struts tend to be more massive than cables.

It is important to realise that any system using the strength of materials to contain energy or transmit loads will be limited by the specific strength, with the particular layout or technique making a difference only of a factor of order unity. At best, a system storing energy as electromagnetic fields within a solid mass could, theoretically, store up to a factor of three times the specific strength, six times as much as the simple flywheel (3D rather then 1D tension gives a factor of three, relativistic field energy rather than non-relativistic kinetic energy a further factor of two); but that is as far as we can go with such techniques. Chemical fuels, such as liquid hydrogen and oxygen, can store similar amounts of energy (~10MJ/kg) only, because similar bond strengths are involved. The most energetic known chemical fuel is monatomic hydrogen, which stores about 200MJ/kg.

Chemical energies are minuscule compared to relativistic energies so the strength of chemically-bonded materials is far below the theoretical relativistic limit of $c^2 = 9 \times 10^{16}$J/kg.

Dynamic structures, supported by the flow of momentum [2-6], do not rely upon the strengths of chemical bonds and can, therefore, have specific strengths approaching the relativistic limit, depending only upon the momentum of the mass-streams that make up the dynamic part of the structure.

Orbital Ring Systems [2-6], orbital towers and similar devices, for use in Earth orbit, have specific energies ~60MJ/kg; a Light-Sail Windmill [4] in close solar orbit ~100GJ/kg; and a pellet-stream propulsion system for relativistic flight ~5×10^{16}J/kg, approaching the relativistic limit.

It is necessary to consider how to apply the techniques of momentum support to high-strength struts and energy storage systems for use with solar sails, magnetohydrodynamic wings, interstellar vehicles and other devices.

2. DYNAMIC COMPRESSION MEMBERS

Figure 1 shows the canonic dynamic compression member or strut. If the relativistic mass line density is m, the mass-stream velocity is v, and the length between reflectors is l, then the compressive force provided is:

$$F = 2\,mv^2$$

The total relativistic mass of the streams is:

$$M = 2\,ml$$

Hence the specific strength is:

$$S = Fl/M = v^2$$

This assumes that the reflector mass is a negligible fraction of the total, which will be true if the strut is sufficiently long.

The specific stored energy is:

$$E = 1 - 1/\gamma \;= v^2/2,\ v \ll c$$

where γ is the Lorentz factor, $(1-v^2/c^2)^{-1/2}$, and where we have divided by the relativistic mass, not the rest mass.

An important feature of this compression member is that, although using streams of mass in rapid motion (hence the term 'dynamic'), it does not use up any energy once set up, except in overcoming losses at the reflectors.

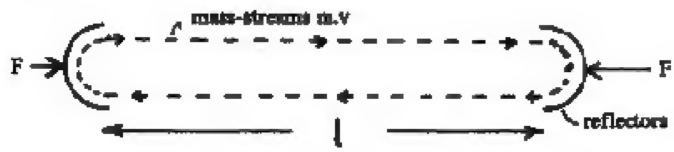


Fig. 1. A dynamic compression member.

The mass-stream could take any convenient form: continuous cable; discrete pellets; plasma; electrons or other sub-atomic particles; light or other electromagnetic radiation. Likewise the reflectors could be an arrangement of superconducting magnets, an active accelerator system or actual mirrors. The essential feature is a highly efficient reversal of the energy and momentum flows.

Orbital Ring Systems utilising dynamic compression members have been analysed in detail [2-6]. As one example consider the Partial Orbital Ring System (PORS), which is like a masonry bridge in which the arch is under pure compression (Fig. 2). In the PORS "bridge" the structure is dynamic, not static, a continuously moving belt or cable, supported by magnets at its "foundations". This is not just a convenient analogy; we could actually use PORS bridges to replace masonry bridges or provide new bridges with enormous spans. In Orbital Ring Systems gravity causes the dynamic compression member to be curved, except in an upward-pointing orbital tower, but the principle is the same as in the canonic strut of Fig. 1 and the analysis above.

There is a circus "conjuring trick" in which a rubber ball bounces up and down between a vibrating table and a china plate, which keeps in the air. This is, of course, a rather inefficient dynamic compression member.

Practical implementations will usually require a reasonably steady force. This could be achieved either with a continuous mass-stream, like a cable, or with a sufficiently large number of pellets of particles to enable the separate impulses to be smoothed out. If the system is not to have too high a power consumption, the mass-stream reversal must be highly efficient i.e., "rubber superballs with a coefficient of restitution very close to unity".

An important component in any practical implementation of a dynamic compression member will be the control and stabilisation system. The canonic dynamic compression member described above is only neutrally stable. If the reflectors act like mirrors, where the angle of incidence equals the angle of reflection, any angular divergence of the mass-streams will be maintained until they are lost to the side. Any misalignment of the mirrors will lead to the same result. Furthermore, dynamic instabilities of the mirror or reversal systems could be caused by off-centred or uneven mass-streams, with behaviour depending on the design of the reflector suspension.

Compression members using electromagnetic radiation, such as light sails, can fairly readily be given an overall directional and positional stability, for example by using secondary mirrors around the periphery of the main beams, but efficient control systems will still be required to adjust the balance across and between the sails.

Other compression members, using cables or discrete mass-streams, may suffer from more subtle forms of instability such as oscillations within and between the streams themselves. Some of these instabilities will be damped out by internal losses, others will be avoided by careful design. However, most practical systems are likely to have certain instabilities that can only be eliminated by active feedback regulated by dedicated electronic control circuits. The processing power required of such systems may be considerable but within the capabilities of current or near-future integrated circuit technology.

The stability of Orbital Ring Systems has been considered in some detail [2] but readers should be cautioned that some of the analysis was in error and that additional instabilities exist which must be countered.

A full analysis of the stability problems of dynamic compression members would be both complicated and strongly dependent upon the specific configuration; it is to be expected that the major part of the effort in designing practical structures using dynamic compression members would have to be expended on it.

3. WING SUPPORT

An arrangement of dynamic compression members can be used to support a compact payload above a large wing; Fig. 3 shows a spanwise section through such a wing. Each mass-stream produces a force balancing the lift on that portion of the wing, thus obviating the need for large-scale structural strength.

The physical strength of the actual wing can be made arbitrarily small by using as many separate mass-streams as necessary. A continuously spread-out mass-stream, such as electromagnetic radiation or stream of plasma, would, theoretically, not require the wing itself to have any strength at all.

The shape and motion of the wing and the relative position of the payload can be controlled by changing the energy and momentum flows in and between the individual mass-streams, or by moving the end-points back and forth.

Such a wing could be used within a planetary or stellar atmosphere, with designs based on the usual aerodynamic forces of lift and drag. A more exciting application would be to an MHD wing, utilising magnetohydrodynamic forces to soar, wheel or decelerate within an ionised interplanetary or interstellar medium. Dynamic soaring in the turbulent interstellar medium and the solar wind could allow unpowered wings or gliders to sail between the stars and planets.

Dynamic soaring is the method that sustains the albatross in its effortless flight [7]. It extracts energy from the relative kinetic energy of regions of air with different wind-speeds in the shear layer near the sea and can reach surprising high speeds, in

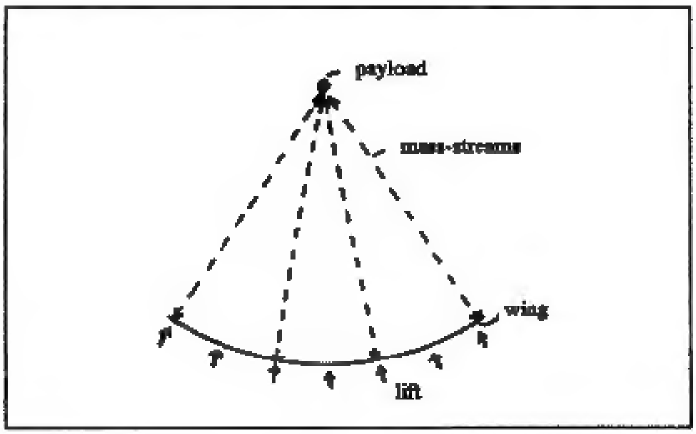


Fig. 3. A momentum-supported wing.

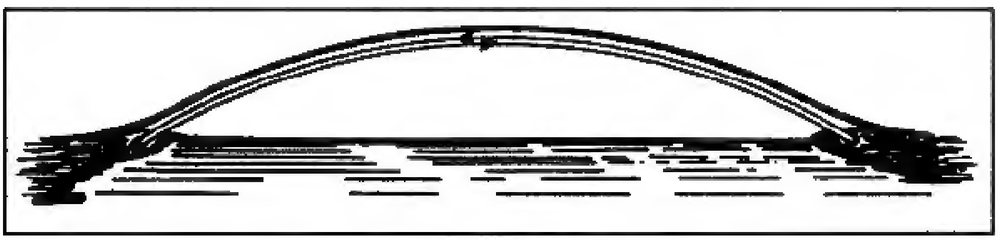


Fig. 2. A PORS bridge.

excess of 60 knots. Other birds use a similar technique in gusty or turbulent conditions.

If the total velocity difference across a shear layer or in gusts of turbulence is ΔV and the bird or glider can achieve a lift-to-drag ratio of L/D, then speeds up to ~(L/D) $\Delta V/2$ can be reached. When we consider that both the solar wind and the interstellar medium have speeds of ~100km/s or more, and that ordinary gliders can have (L/D)~60 it is clear that there is an opportunity for MHD gliders to reach speeds of at least .02c. Indeed, since the solar wind is largely a collisionless medium there is reason to believe that an MHD wing could eliminate frictional drag, thus achieving very much higher values of (L/D), and perhaps even relativistic speeds. A "Starglider" interstellar vehicle, propelled by free-ranging MHD wings, and accelerating to relativistic speeds at a continuous one gee (10m/s^2), is an exciting possibility.

4. LIGHT-SAIL SUPPORT

Like wings, light-sails also can be supported by dynamic compression members (Fig. 4). If light is reflected from the sail as shown, the light pressure acts inwards, along the line of the struts to the main payload. Limits on the concentrated mass of payloads and on the size of sails can thus be overcome. The geometry of this system is the opposite to that of a conventional light-sail with cables. As with dynamically supported wings, control is maintained by manipulating the component mass-streams.

The simplest arrangement to construct is probably one which uses oncoming light itself as the medium for dynamic support, by directing most of the light inwards to a mirror at the central payload, with just enough directed sideways to balance the momentum flow. Control of the sail is provided by changing the amounts of light sent off in various directions at each part of the sail.

The efficiency of this method as a means of support for the light-sail is rather high, especially when the oncoming light is well-collimated. The relative ease with which it could be constructed and controlled make it an attractive possibility.

Figure 5 shows an arrangement of mirrors suitable for a light-sail supported by the light itself. The component mirrors can be as small as is convenient and can be arranged in an annular fashion around a central axis. Figure 6 is a detailed diagram of the sail geometry. Figure 7 shows a suitable form for the overall geometry, giving an indication of the effect of the finite angular size of the Sun.

It will be observed in Fig. 5 that the light falling upon the upper mirror (AB) is immediately reflected away, but the light falling

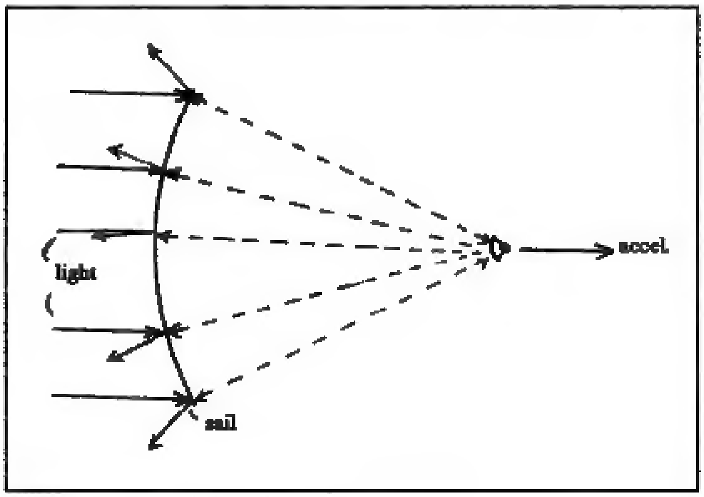


Fig. 4. Geometry for light-sail support.

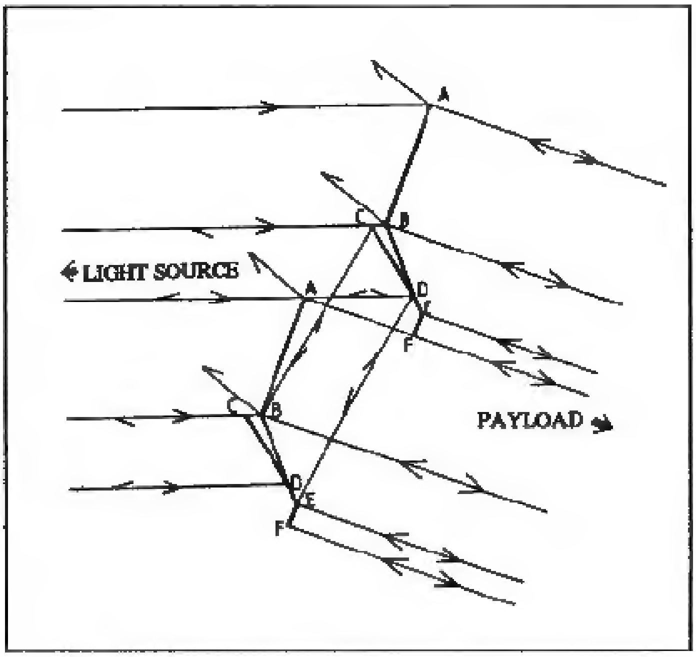


Fig. 5. Light-sail mirror geometry.

upon the lower mirror (CD) is directed in towards the payload mirror. Once between the light-sail and the payload, the light is trapped into bouncing back and forth until it finds its way back out the way it came. It must be emphasised that the collimation of the light and the mirror surfaces need not be exact; the light does not have to exit through exactly the same slot it entered by; it is the average light flux that counts.

We may calculate the thrust generated by such a light-sail, compared to the thrust on a black body of equivalent projected area (the thrust on a perfect mirror at right angles to the light is then two units). For simplicity, we shall assume perfect mirrors and a point light source. More detailed calculations would need to consider finite reflection coefficients and finite angular sizes. The mirrors AB are set normal to the direction of the payload at an angle α; they are double-sided. The mirrors EF, CD and BE are set at angles α, β and γ, respectively and can be single-sided.

From the detailed mirror geometry of Fig. 7 we may obtain the following equations:

$$\gamma = \alpha/2+\beta$$
$$y_1 = x_1/\cos\alpha$$
$$y_2 = 1-x_1$$
$$x_2 = y_2\cos(\alpha+\beta)/\cos\beta$$
$$x_3 = y_3\cos\alpha$$
$$z_1 = x_1\tan\alpha$$
$$z = (1-x_1)(\tan(\alpha/2+\beta)-\tan\beta) + 1/\tan(\alpha+2\beta)$$
$$y = \cos\alpha + z\sin\alpha$$
$$y_3 = y-y_1-y_2$$

Now the side force on the mirrors is:

$$F_1=x_1\sin(2\alpha)$$

This must be countered by the sideways component of the force between mirrors and payload. This force is therefore:

$$F_2=F_1/\sin\alpha = 2x_1\cos\alpha$$

The forward force on the payload is therefore:

$$F_3 = F_2\cos\alpha = 2x_1\cos^2\alpha$$

The total forward force is given by:

$$F_4 = x_1(1+\cos(2\alpha))+(1-x_1)(1+1)$$

$$F_4 = 2(1-x_1\sin^2\alpha)$$

and the forward force on the mirrors is:

$$F_5 = 2(1-x_1\sin^2\alpha)-2x_1\cos^2\alpha$$
$$F_5 = 2(1-x_1)$$

The force generated by the light bouncing back and forth between mirrors and payload is given by the following sum:

$$F_2 = (1-x_1)\ (1+(1-y_2/y)+(1-y_2/y)^2+(1-y_2/y)^3+...)$$
$$F_2 = (1-x_1)/(1-(1-(1-x_1)/y))$$
$$F_2 = y$$

Thus:

$$y = 2x_1\cos\alpha$$
$$x_1 = (1+z\tan\alpha)/2$$
$$x_1 = (1+((1-x_1)\ (\tan(\alpha/2+\beta)-\tan\beta) + 1/\tan\ (\alpha+2\beta))\tan\alpha)/2$$
$$x_1 = 1 - (1-\tan\alpha/\tan(\alpha+2\beta))/(2-\tan\beta + \tan(\alpha/2+\beta))$$

This expression for x_1 can be evaluated for given α and β, then used to calculate y and z; and thus obtain y_3, which must be positive for a physical solution.

The area or mass of the mirrors and the corresponding payload mass is then given by:

$$m_m = y_1+y_3+(1-x_1)/\cos(\alpha/2+\beta)+x_2/\cos\beta$$
$$m_m = 2x_1\cos\alpha+(1-x_1)(\cos(\alpha+\beta)\cos^2\beta+1/\cos(\alpha/2+\beta)-1)$$
$$m_p = m_m F_5/F_3$$

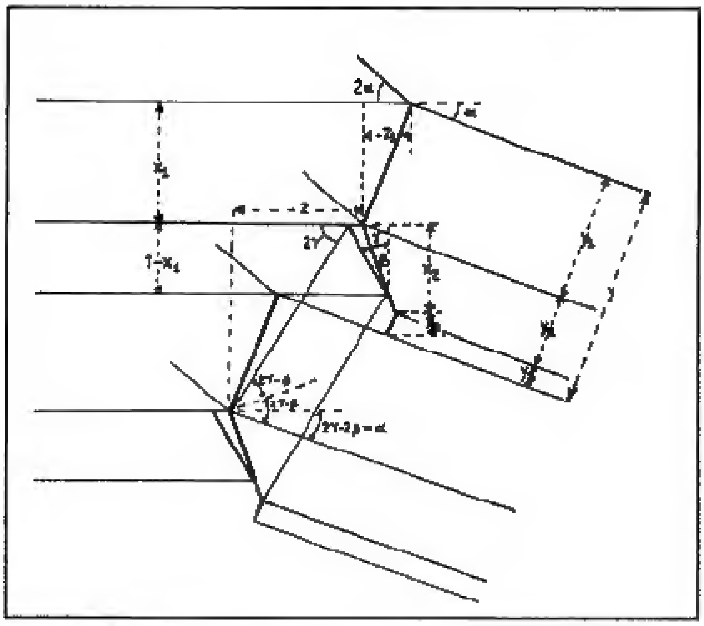


Fig. 6. Detailed mirror geometry.

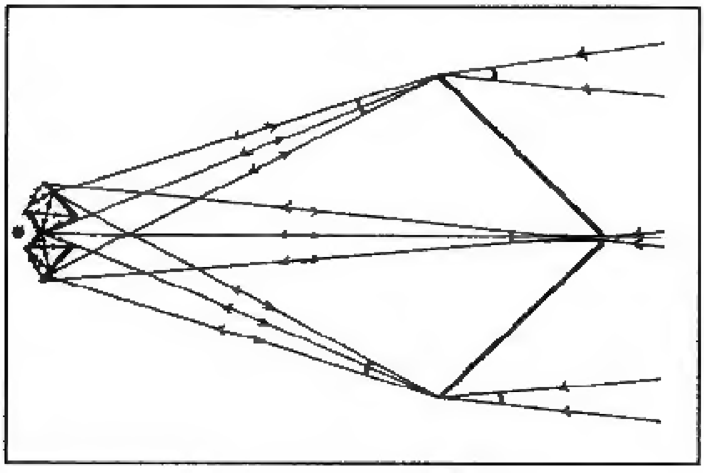


Fig. 7. A solar-sail with a source of large angular size.

We now can vary α and β in search of a maximum in the ratio of forward force to mass and try to find the maximum possible acceleration for a given mirror mass and payload mass per unit area.

Computer analysis shows that over a range of angles α in the range 0° to 45° accelerations of about 0.55 units can be achieved (where a bare sail normal to the light would achieve up to 2 units) with a payload fraction of about 60%. Figure 8 shows this in more detail.

It should be noted that not all combinations of α and β lead to physically realisable solutions in which the accelerations of the sail and the payload are the same. The unrealisable cases are when $y_3<0$ in Fig. 8h. These regions have been excised from the remaining graphs. When β >90°-2α the geometry changes slightly, with the mirrors CD moving back, and BE and EF moving back and down relative to AB.

Figure 8a shows that the acceleration is highest for a range of β around 10°-40°, where the efficiency of utilisation of sail material (Fig. 8d) is also high. In this region the mirror mass (Fig. 8c) is low and the mirror mass fraction (Fig. 8b) has a reasonable value. It is apparent that values of β>60°, say, should be avoided and that small values of α are to be preferred, where angular-size constraints permit.

One may note that, with this geometry, the mirror mass never exceeds the payload mass, that x_1 always lies between 1/2 and 1 and that y lies between 1 and 2. The behaviour of z (Fig. 8g), which determines the overall shape of the sail, is also interesting. When β is around 45° it is near zero, corresponding to a sail extended at right angles to the light source. As α increases above 17°, forcing β to decrease below 45°, z must become positive and, in effect, the sail bends away from the light. However, for small α, and β>45°, z can be negative, so that the sail slants the opposite way.

Putting this together, Fig. 9 shows a possible compromise geometry that might be suitable if a sail of moderately short focal length is required.

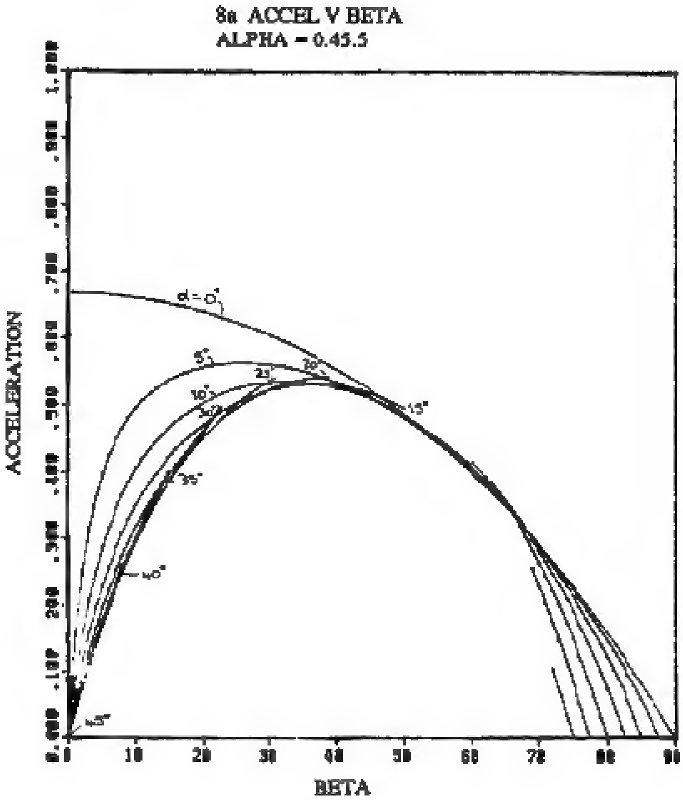
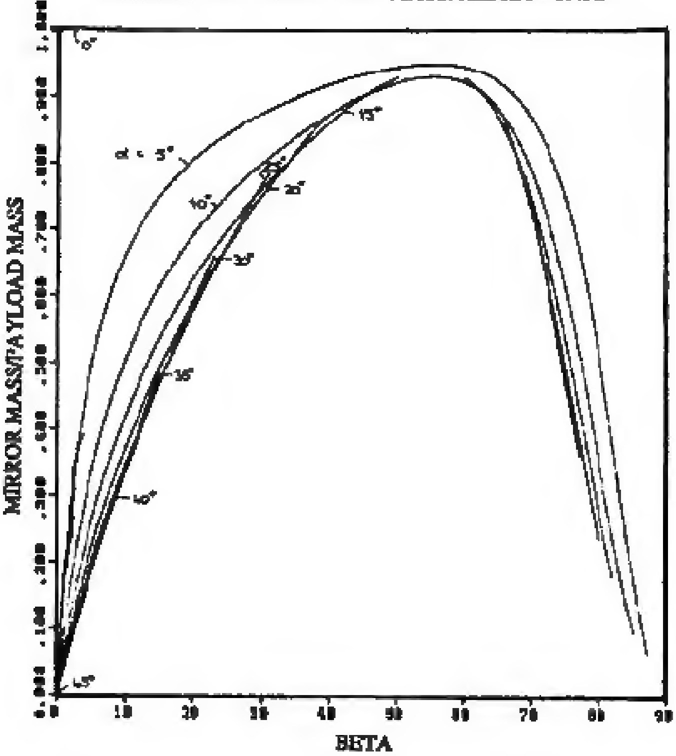
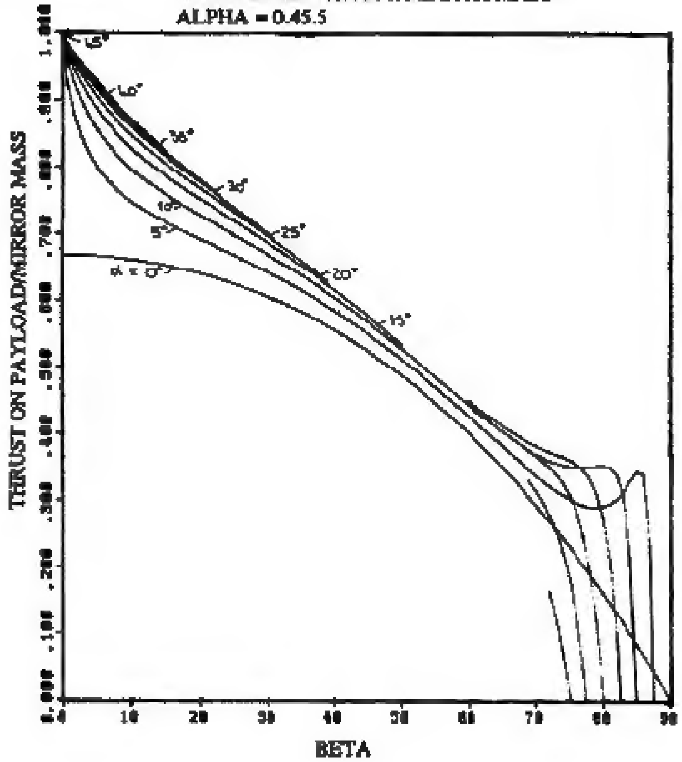


Fig. 8. Graphs of various light-sail parameters.

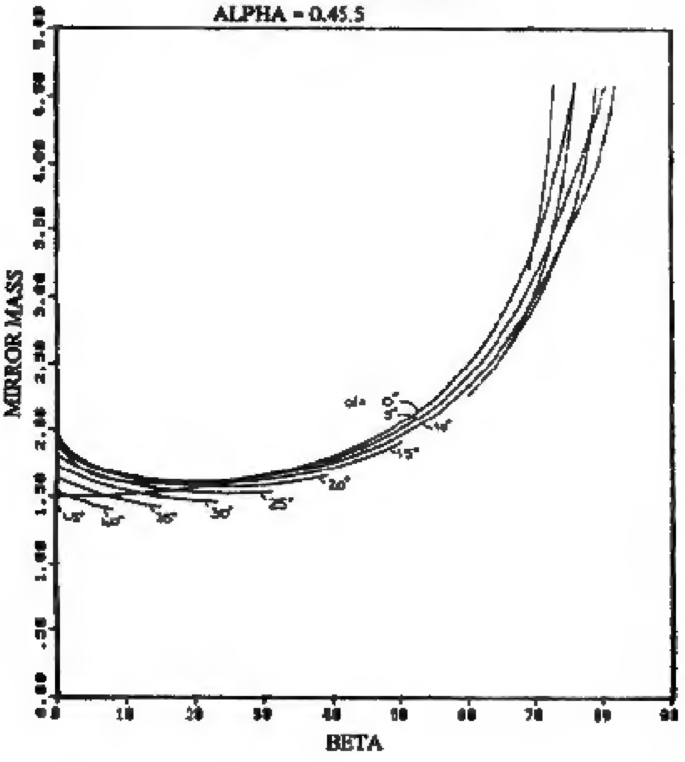
8b MIRROR MASS/PAYLOAD MASS: ALPHA = 0.45.5



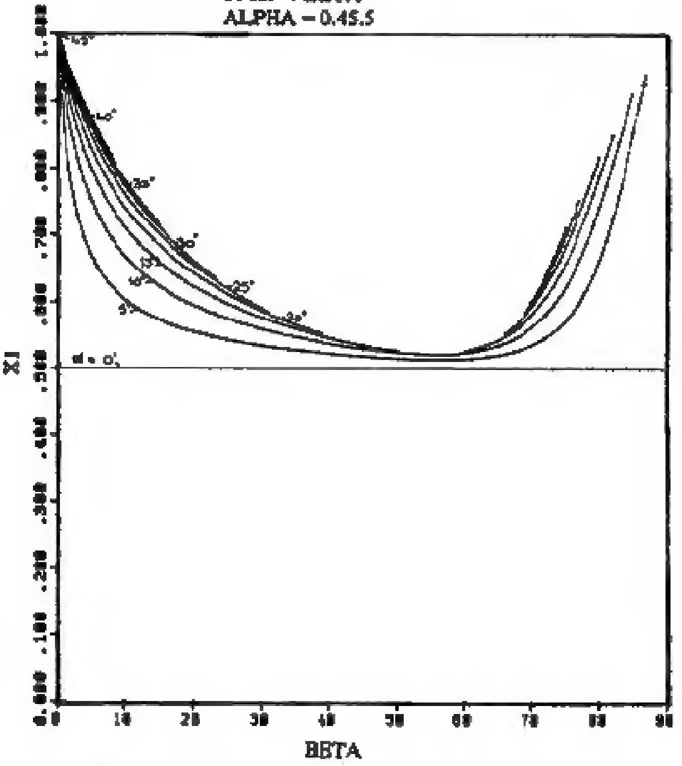
8d PAYLOAD THRUST/MIRROR MASS
ALPHA = 0.45.5



8c MIRROR MASS V BETA
ALPHA = 0.45.5



8e XI v BETA
ALPHA = 0.45.5

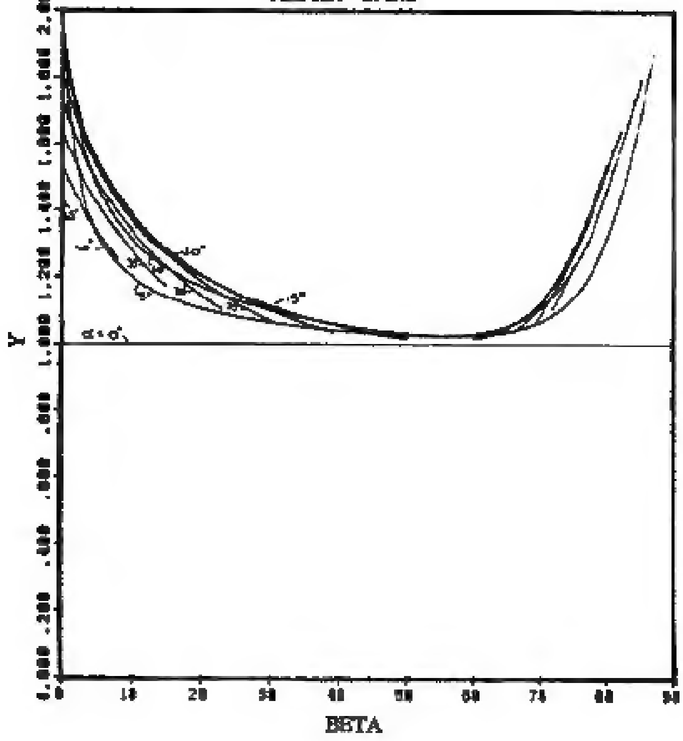


Higher accelerations are possible at the expense of smaller payload fractions, if the light sail is thinned and the dynamic compression member weakened. This could be achieved by removing the mirrors EF or by leaving spacing gaps, so that the sails use more of the total thrust.

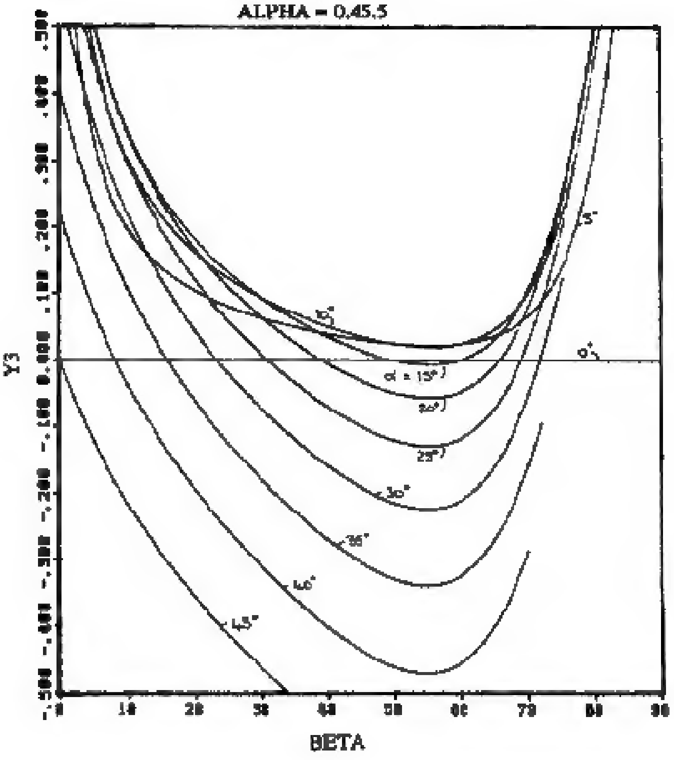
The above geometry is not necessarily optimal. Nevertheless, it demonstrates an efficient and versatile system which would be simple to manufacture and in which the accelerating forces can be controlled and the side forces balanced out simultaneously. The light bouncing between the main sail and the payload acts as a dynamic compression member of more than enough "strength" to support the sail. It should be noted from Fig. 8a that the sail acceleration can be made negative for negative β, i.e., the sail can, if desired, be pushed backwards away from the payload.

Light-sail performance could be improved if the light-sail could be used as a converging lens placed considerably closer to the light source than the payload. A single conventional lens

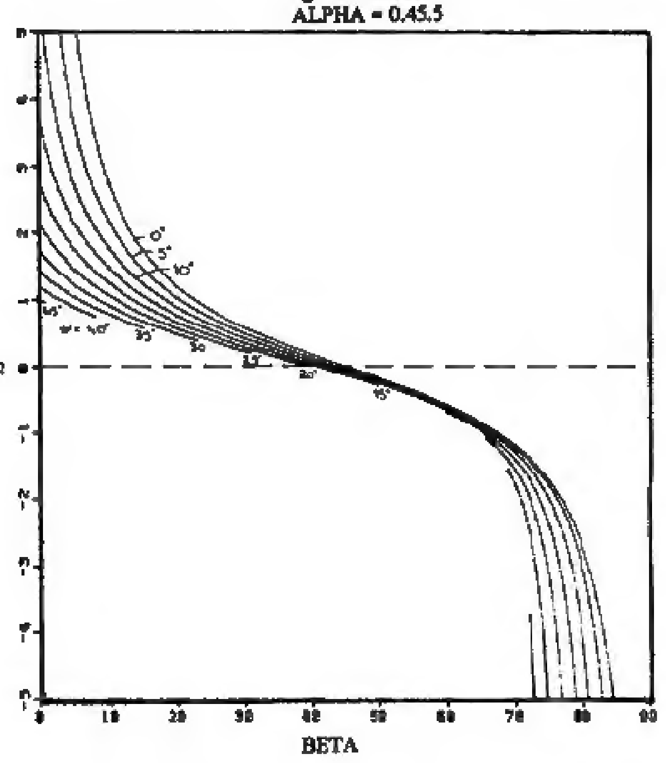
8f Y v BETA
ALPHA - 0.45.5



8h Y3 V BETA
ALPHA = 0.45.5



8g Z v BETA
ALPHA = 0.45.5



has a fixed focal length and multiple lenses are necessary to adjust the focus. These lenses can be many wavelengths thick and correspondingly massive. A Fresnel lens can be much less massive but suffers from chromatic aberration. Yet even a very thin refraction lens will be a few microns thick and have an areal density of a few grams per square metre, which is massive by light-sail standards.

A very light reflection lens can be constructed on the Fresnel principle by alternating reflecting rings with empty transmitting rings (Fig. 10). Half of the light is reflected and half transmitted from either direction. About half the transmitted light converges at the focal point. If the reflectors are accurately positioned the cavity between lens and focal-point reflector forms a dynamic compression member in which the net force on the mirrors is about 0.6 or $(1\text{-}4/\pi^2)$ and the forward force on the payload approaches 0.8 or $8/\pi^2$ (normalised as above). Since the lens filling factor is only 1/2, this corresponds to an acceleration of 1.2 for a mirror mass only 3/4 the payload mass.

This is an efficient light-weight system which can be given even higher accelerations at the cost of an increased mirror mass ratio. If the light coming back from the payload reflector is aimed to pass outside the sail without hitting it, then the forward force on the sail becomes 1 and at the payload 0.4, giving an acceleration of 2 and a mirror mass 2.5 times the payload mass. This acceleration is the same as that of a bare sail.

This is not the limit. If we micro-perforate the sail material, in the filled portions of the lens, with holes about half a wavelength across, bringing the overall filling factor down to 1/4, we find that the little holes scatter back (i.e. reflect) about half the light incident upon them. The sail as a whole then reflects back about 3/8 the incident light, leading to an acceleration of three units. The light "leaking" through the sail could reduce the thrust at the payload to 0.3, so the mirror mass would then be 10 times the payload mass for equal acceleration.

Micro-perforated sails also cause a phase-delay in the light leaking through them. In effect, the reflecting or conducting portions create an artificial dielectric about a wavelength deep. The phase shift can be of order π radians and will vary according to the filling factor and the shape of the holes. This property could be used to increase the focusing efficiency of reflective Fresnel lenses by providing the correct phase distribution across the lens aperture, thus increasing the thrust at the payload.

Even this is not an absolute limit. We may consider a sail as equivalent to a radio antenna and design it as a network of slots and short dipoles, or as a web of metallic strands. In fact, a

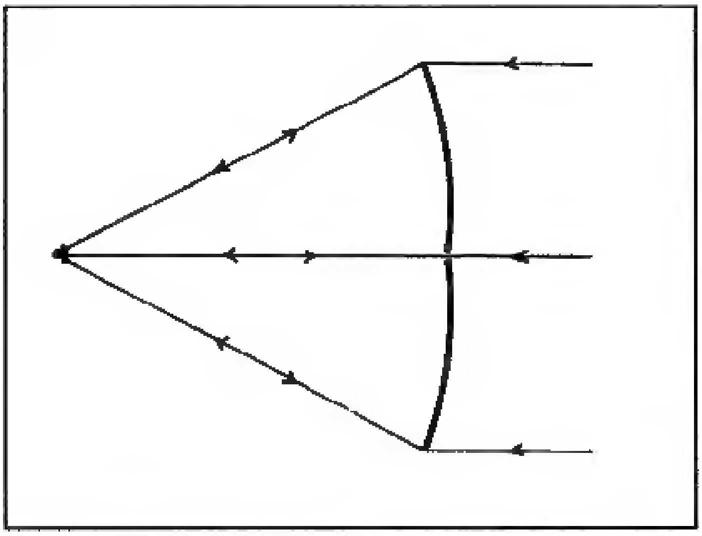


Fig. 9. A convenient shape for a light-sail.

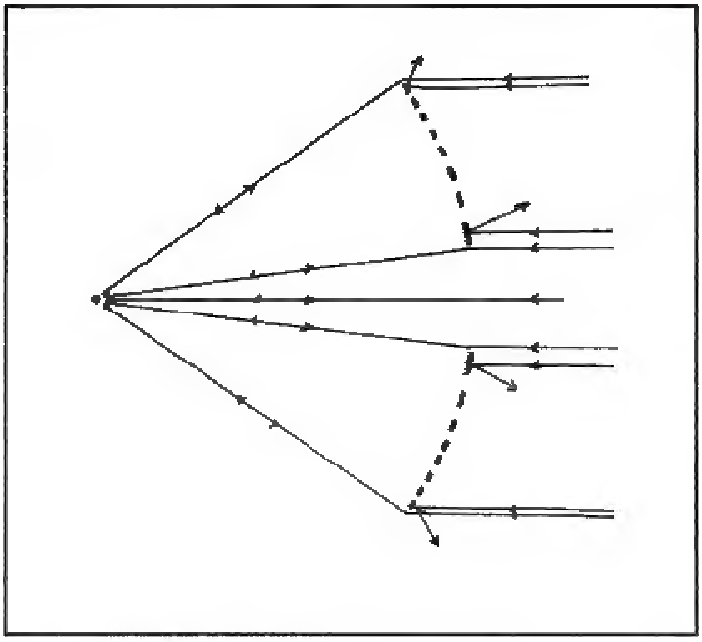


Fig. 10. A reflecting Fresnel lens.

suitably designed sail, with a hierarchy of gaps and perforations, could have arbitrarily low filling factors, with no theoretical upper limit on the ratio of the effective reflecting area to the filled area. Other limits on the absolute acceleration can arise, but only at enormous values $>10^{12} ms^{-2}$, which will rarely be applicable. There are practical limits, however, due to losses in the sail material. A sparsely-filled web can reflect in the gaps only by virtue of a reactive field reaching out to the reflecting strands. The lower the filling factor, the more energy has to be stored in the reactive field and the greater the ratio of the energy stored to the energy being reflected. Then the losses must be lower and the Q-factor higher to sustain the field. For broad-spectrum visible light and common materials this Q-limit is severe and net accelerations much in excess of three units are unlikely. This is directly related to the difficulties in applying more than a few dBs of "supergain" to radio antennas [8].

Although reflective Fresnel lenses can be made very efficient they have the disadvantage of producing chromatic aberration when used to focus light from the Sun. The effects of this aberration can be reduced, though not eliminated, by using multiple Fresnel lenses "tuned" to different wavelengths in a complex optical system. Since the focal length of the Fresnel lens varies with wavelength, it is possible that an arrangement of relatively small lenses in the focal region may be able to adjust the chromatic aberration without a major increase in the total mirror mass. The use of a laser light-source also solves the aberration problem. The finite angular size of the Sun may also cause difficulties, and the focal length of a Fresnel lens sail would not be easy to adjust in flight.

Lenses utilising light-sails in the geometry of Fig. 6 can be wavelength independent because the light paths through the mirrors introduce fixed delays. The mirror rings can be made arbitrarily narrow and the path lengths controlled to a fraction of a wavelength. They can also be adjusted to vary the focal length as the starship accelerates.

Unfortunately, to get a major improvement in performance the sail must capture more light by staying nearer to the Sun than to the payload, and the angular size of the Sun will widen the focus point excessively. Two solutions suggest themselves. First, to use a laser or other physically compact light-source so that a sharp focus can be achieved, using Fresnel reflection optics for efficiency; second, to use an enormous light-sail larger in diameter than the Sun, say $10^{19} m^2$ at $10^{-7} kg/m^2$, amounting to 10^{12}kg of sail and a reasonably small mass for a worldship.

It is apparent that light sails with geometries similar to the above can utilise thin-film mirrors very efficiently, whilst avoiding the constraints on maximum payload mass due to the strength limitations of conventional structures. It is also clear that considerable dynamic reconfiguring of such sails for acceleration and trajectory control would be feasible.

We may mention the proposed laser-pushed light-sail mission to Barnard's star [9]. Problems arose in that scenario because of the large mass of the refracting Fresnel lens in the Solar System. A reflective lens would use much less material and could be made that much bigger. Use of the main light-sail during the deceleration phase as an optically precise mirror adjusted to within about 1μm in 10km, would also be difficult. Figure 11 is a suggested arrangement which uses a reflecting lens as the main sail. The light focused on the payload is transmitted through the lens. Thus only the local phase-delay matters, not the exact overall shape of the sail. This would be simpler to engineer than an optically perfect mirror and would enable the deceleration phase to be spread over a greater distance.

5. ENERGY STORAGE

Any dynamic compression member is also an energy storage system; this is apparent from the analysis in section 2, from which we see that the energy stored per unit force generated is:

$$
\begin{aligned}
H = 1\,(1-1/\gamma)/v^2 &= 1/2, \quad v<<c \\
&= 1, \quad \gamma>>1
\end{aligned}
$$

The energy is greater for relativistic streams or electromagnetic radiation and increases with length without limit. Provided that sufficient force can be applied at each end to hold the system together, the energy could be stored indefinitely, excluding turn-around losses. The force could be gravitational, as in an ORS, or generated by the inertia of a sufficiently large mass.

As an example, consider a relativistic storage system ($\gamma >> 1$ or v=c) set up between Earth and a similar planet orbiting α-Centauri ($l=4 \times 10^{16}$m). The line density can be a modest 1kg/m (the rest-mass line density is even smaller by a factor γ). The force generated is then 2×10^{17}N ($2mv^2$), which could be applied to the Earth by a band 10m wide around its circumference. The energy stored is 8×10^{33}J ($2mv^2 l$), amounting to the entire power output of the Sun for eight months!

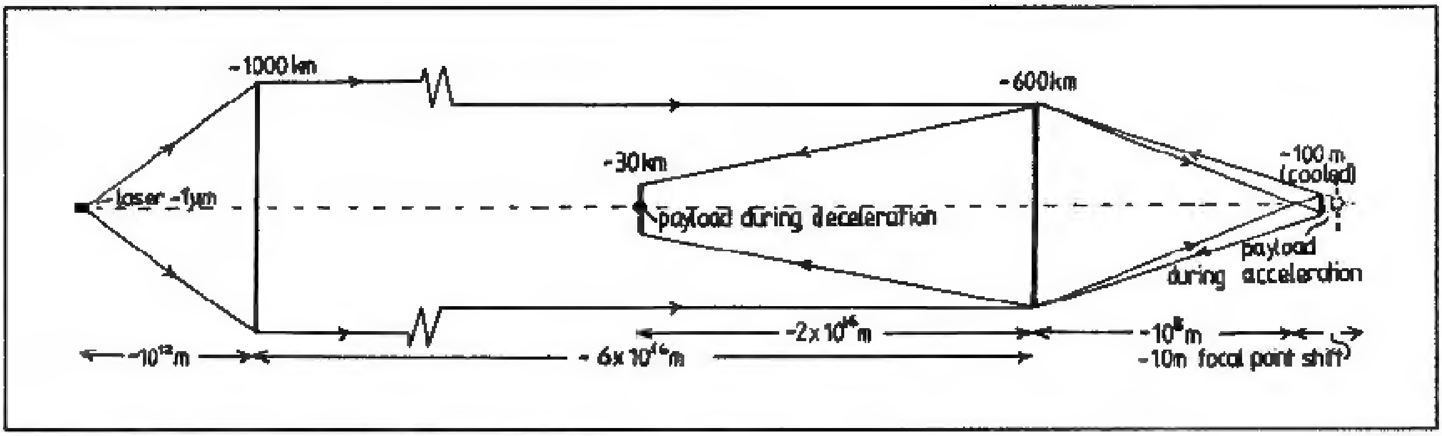


Fig. 11. A light-sail arrangement for deceleration.

Relativistic electron beams can maintain their diameter without dispersion in the interstellar medium and would be suitable for such systems. Vehicles (startrams) could accelerate to relativistic speeds along these tracks utilising the stored energy and transferring momentum to the mass-streams.

On-board dynamic energy storage for starships pose more difficult problems. On the one hand, a compression member contained by strong materials would be limited in net specific energy (section 1). On the otherhand, an unconstrained member would soon fly apart. Useful energy can, however, be stored by allowing relative accelerations between different (massive) parts of the starship assembly, e.g., between the payload and a light sail, and manipulating the compression forces and the thrusts to keep a planned balance.

A lens-sail of very large diameter, or one using laser light, which can be allowed to accelerate more slowly than the payload for the early part of the flight, has the dynamic compression member as an energy store used to maintain extra payload acceleration as the light flux falls. A considerable improvement in the final payload velocity is possible, especially in the laser-driven case.

However, it is unlikely that such mirror arrangements would be suitable as general-purpose energy storage systems except perhaps for very short periods, unless very great path-lengths could be employed, since reflection coefficients in excess of ~95% would be hard to achieve.

For the purpose of energy storage a higher reflection efficiency than is possible with visible light would be desirable. Such an improvement could be achieved by using the mirrors, in the geometry of Fig. 4, as an RF cavity, at a sufficiently low frequency where power is easy to generate efficiently and where extremely high reflection coefficients or Q-factors may be obtained. Alternatively, streams of pellets at some conveniently high velocity may be employed.

Such a system would store energy more like a spring than a battery. One could not simply charge it up and leave it alone until one wished to use it; all its component parts would be in dynamic balance, continually changing. All the accelerations, and all the energy, mass and momentum flows must be calculated for each application over the whole of the relevant period. These calculations will easily become very complex.

An energy storage system, using additional ballast mass, could mitigate the initial high accelerations of the light-sail payload near the Sun, increase the total energy collected by holding the sail itself closer to the light-source while the payload accelerates out, and accelerate ballast mass using the stored energy to gain additional thrust as the light flux falls. Light-sail missions of the kind considered in [10] could be implemented.

Improved performance and more varied capabilities could be achieved in more complex systems with multiple stages; or with paired mass-streams, using one high velocity stream (say, electromagnetic radiation) and one slower (say, pellets) for independent control of energy, mass and momentum flows.

6. CONCLUSIONS

Dynamic compression members offer hope where conventional structures could not be given sufficient mechanical strength, or where chemical energy is not enough. Strengths up to the relativistic limit of 9×10^{16}Nm/kg, and energy storage up to 9×10^{16}J/kg are feasible.

Dynamic compression members, under active control, can be given whatever structural properties are desired. Long thin struts will not buckle; they will not break under high stress; their length is variable through any range; they can react with a precisely defined force; and their effective Young's Modulus can be set to any value.

If one employs active feedback to maintain a precise length, the value of the Young's Modulus will become effectively infinite; it could equally well be made negative.

Dynamic compression members can also store large amounts of energy, increasing the potential capabilities of any structure using them.

Dynamic compression members can be used to support large thin-film lenses, light sails and magneto-hydrodynamic wings.

In conclusion, techniques employing dynamic compression members are likely to be of value in the construction of large structures in space, including composite solar sails and interstellar vehicles.

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